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Effects of double cropping on summer climate of the North China Plain and neighbouring regions

Su-Jong Jeong[1], Chang-Hoi Ho[2]*, Shilong Piao[3,4], Jinwon Kim[5], Philippe Ciais[6], Yun-Bok Lee[2], Jong-Ghap Jhun[2] and Seon Ki Park[7,8,9]

The North China Plain (NCP) is one of the most important agricultural regions in Asia and produces up to 50% of the cereal consumed in China each year[1,2]. To meet increasing food demands without expanding croplands, annual agricultural practice in much of the NCP has changed from single to double cropping[3,4]. The impact of double cropping on the regional climate, through biophysical feedbacks caused by changes in land surface conditions, remains largely unknown. Here we show that observed surface air temperatures during the inter-cropping season (June and July) are 0.40 °C higher over double cropping regions (DCRs) than over single cropping regions (SCRs), with increases in the daily maximum temperature as large as 1.02 °C. Using regional climate modelling, we attribute the higher temperatures in DCRs to reduced evapotranspiration during the inter-cropping period. The higher surface temperatures in June and July affect low-level circulation and, in turn, rainfall associated with the East Asian monsoon over the NCP and neighbouring countries. These findings suggest that double cropping in the NCP can amplify the magnitude of summertime climate changes over East Asia.

Unlike the global trend of increasing cropland areas[5], the cropland area in the North China Plain (NCP) has decreased by 30% over the past five decades (Fig. 1a) as a consequence of policies such as the world's largest land set-aside program 'Grain for Green'[6] for curtailing soil erosion in China's major river basins. To compensate for the reduced crop production due to less farming area, wheat-maize double cropping has expanded, along with irrigation and fertilization. These changes in agricultural practice are very successful in terms of increased crop production in the NCP (refs 2,7). For example, the annual crop yield has increased by 30% over the past 16 years, mainly owing to the cultivation of maize, which is grown in rotation with wheat[8] (Fig. 1b). Considering that this cropland management practice accounts for over 50% (33%) of the total wheat (maize) production in China, it is evident that double cropping plays a crucial role in China's food production because crops produced in the NCP region feed 22% of the Chinese population[4].

The environmental consequences of changing the agricultural practice from single to double cropping in such a vast area remain to be understood. Double cropping results in two growing seasons separated by a post-harvest/pre-planting (that is, inter-cropping) period in which soils are either left bare or partially covered with harvest residues[9]. Thus, the altered surface characteristics caused by switching from single to double cropping practice affect the regional energy budget in the inter-cropping period. The inter-cropping period also corresponds to the peak monsoon season over East Asia[10]; thus, the effects of changes in land management on the surface energy budget over such a large land area may also affect some characteristics of the monsoon circulation. This study aims to understand the effects of double cropping in the NCP region on the circulation and climate in the East Asia region during the inter-cropping period.

The NCP region is defined here as the region covering the northeastern part of China bounded by 30°–40° N and 112°–122° E. Most double cropping regions (DCRs; filled circles) are located in the central part of the NCP, whereas single cropping regions (SCRs; open circles) are located on the outskirts of the NCP region (Fig. 2a). First, we examine the differences in the observed daily mean (T_{mean}), maximum (T_{max}) and minimum (T_{min}) temperatures, as well as the diurnal temperature range (DTR, T_{max} minus T_{min}) between SCRs and DCRs for the inter-cropping period averaged over 1985–2005 (Fig. 2b). We then investigate the mechanism behind the temperature difference between DCRs and SCRs in a regional climate model experiment. Two runs of the Weather Research and Forecasting (WRF) model have been performed by implementing two different annual crop cycles; the control (CTR) run assumes 100% single cropping, and the experiment (EXP) run assumes 100% double cropping in the entire NCP region (see details in Methods).

Averaged over the past two decades (1985–2005), the observation shows that T_{mean} in the inter-cropping period is higher for DCRs than for SCRs by 0.40 °C ($p < 0.05$; Fig. 2b). This difference in T_{mean} during the inter-cropping period is mainly related to the higher average T_{max} over DCRs than over SCRs by 1.02 °C ($p < 0.01$). Compared with the T_{max} difference between these two regions, the difference in nighttime T_{min} between DCRs and SCRs is −0.28 °C ($p > 0.05$). This is smaller than the magnitude of the T_{max} difference, as well as being negative. The increase in T_{max} and the decrease in T_{min} result in a larger diurnal temperature range over DCRs than SCRs by 1.30 °C ($p < 0.01$). These observational analyses suggest that bare soil partly covered with crop residues during the

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91011, USA, [2]School of Earth and Environmental Sciences, Seoul National University, Seoul 151-747, Korea, [3]Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China, [4]Laboratory of Alpine Ecology and Biodiversity, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China, [5]JIFRESSE and Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California 90095, USA, [6]Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, CE l'Orme des Merisiers, 91191 Gif sur Yvette Cedex, France, [7]Department of Environmental Sciences and Engineering, Ewha Womans University, Seoul 120-750, Korea, [8]Department of Atmospheric Science and Engineering, Ewha Womans University, Seoul 120-750, Korea, [9]Center for Climate/Environment Change Prediction Research, Ewha Womans University, Seoul 120-750, Korea. *e-mail: hoch@cpl.snu.ac.kr

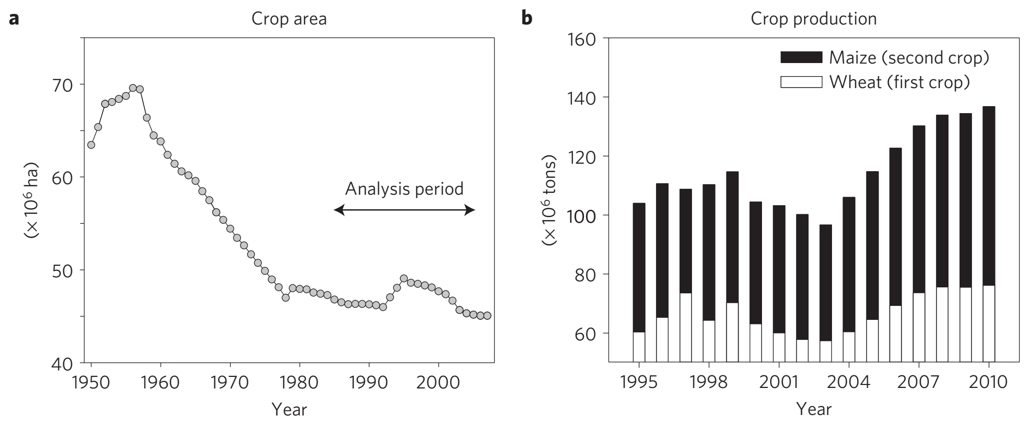

Figure 1 | Changes in crop area and yield. a, Historical changes in crop area over the NCP regions for the period 1950–2007. **b**, Observed total crop (wheat and maize) yield (tons) over the NCP for the period 1995–2010.

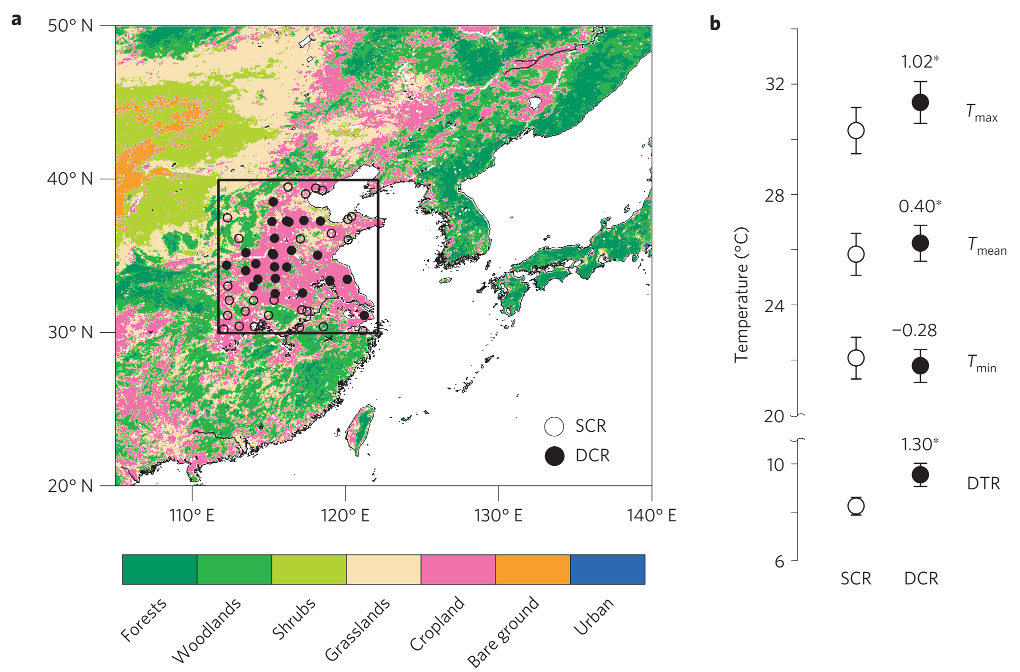

Figure 2 | Warming in double cropping regions during the inter-cropping period (June and July). a, Land cover types and location of double cropping regions (DCRs; filled circles) and single cropping regions (SCRs; open circles) over East Asia. **b**, Observed climatology (1985–2005) of T_{mean}, T_{max}, T_{min} and DTR over DCRs and SCRs, respectively. Numerical values on the figure denote the differences between values of T_{mean}, T_{max} and T_{min} in DCRs and SCRs. The asterisk indicates statistical significances at a 95% confidence level. Error bars on the dot indicate the standard deviations of T_{mean}, T_{max}, T_{min}, and DTR between stations within DCRs and SCRs, respectively.

inter-cropping period of June–July leads to an increase in T_{max} as a result of reduced evapotranspiration. Transpiration by live vegetation cools vegetated surfaces in the daytime[11,12]. Thus, the reduced transpiration due to diminished live vegetation mass can explain the higher T_{max} in the inter-cropping period. The observed temperature differences between these two different types of crop management site may also be attributed at least partially to other local factors, such as irrigation, urbanization, aerosols, cloudiness and geography. The regional modelling study discussed below is designed to examine the impact only of these two different cropping practices on regional temperatures and atmospheric circulation through the associated differences in surface vegetation characteristics.

The differences in the simulated surface temperature and heat fluxes between CTR and EXP averaged over the SCRs (open circle) and DCRs (filled circle) identified in Fig. 2a for the 21-year period 1985–2005 (Fig. 3) are consistent with observations (Fig. 2b), at least qualitatively. Numerical values are the differences between the two experiments (that is, EXP minus CTR). Over SCRs, T_{max} in EXP exceeds that in CTR by 0.31 °C. The T_{mean} difference of 0.23 °C and the DTR difference of 0.16 °C are mainly due to the T_{max} difference (Fig. 3). The latent heat (LH) flux in EXP is smaller than that in CTR by 5.53 W m^{-2}, whereas the sensible heat (SH) flux in EXP is larger than that in CTR by 4.22 W m^{-2} (Fig. 3). The effects of albedo differences on the simulated temperature and heat flux differences are small (<2%), although the albedo is slightly lower in EXP than in CTR because of the lower leaf area index (LAI). These results indicate that the bare soil/plant residues covering the land surface during the inter-cropping period (June–July) reduce evaporative cooling, resulting in higher temperatures than those over vegetated surfaces. This suggests that surface temperature will increase via the changes in LH and SH when agricultural practices are changed

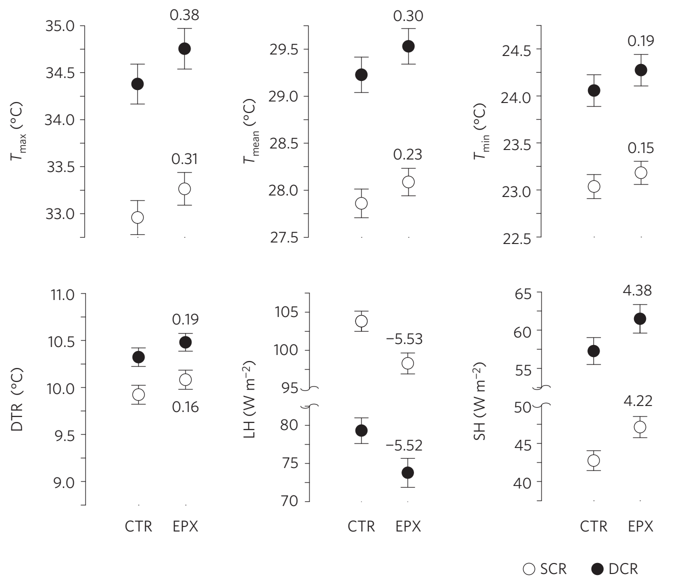

Figure 3 | Differences of simulated temperatures and surface fluxes between control (CTR) and experiment (EXP) over the double cropping regions (DCRs) and single cropping regions (SCRs) on the NCP. Difference between simulated temperatures (T_{mean}, T_{max}, T_{min} and DTR) and surface fluxes (latent heat (LH) and sensible heat (SH)) in the CTR and EXP over SCRs and DCRs, respectively.

from single cropping to double cropping. Readings at the DCRs show similar positive temperature differences to those at the SCRs. These results indicate that despite the representation of the effects of agricultural practices in the WRF model being largely qualitative, the modelling experiment has generated statistically significant temperature sensitivities that are consistent with the observations. The differences in the magnitude between the simulation and the observation may be related to model errors and/or scales (Supplementary Information).

Surface warming over the NCP due to double cropping is expected to induce changes in large-scale circulations through anomalous surface heating. This is because a change in the nature of the land surface over such a large and homogeneous area (812,268 km^2) acts as a forcing agent in the synoptic-scale atmospheric circulation[13,14]. During the inter-cropping period, the East Asian summer monsoon (EASM) system is generally located around the NCP region[10,15] (Supplementary Fig. 2), so that a change from single to double cropping has the potential to have a considerable impact on regional-scale circulation and precipitation. It is, however, difficult to estimate the impacts using only surface observations. Therefore, we evaluate the potential impacts of a change in cropping practices on regional large-scale circulation and climate over East Asia by comparing the CTR and EXP simulations. For the entire simulation period, we examine the impact of double cropping on circulations for the 21-year climatology, and for abnormal years such as strong and weak EASM years (see details in Methods).

The precipitation and circulation differences between CTR and EXP for the entire 21-year period (Fig. 4) indicate that double cropping affects precipitation beyond its regional boundary, especially in strong EASM years. A notable reduction in precipitation occurs over Korea, by −2.1 mm d^{-1} in response to double cropping (Fig. 4b). However, precipitation over Japan is enhanced by +2.3 mm d^{-1}. The prominent changes in strong EASM years compared with weak EASM years, as well as the climatology, are attributed to the difference in the seasonal rain band position over East Asia (Supplementary Fig. 2). For strong EASM years,

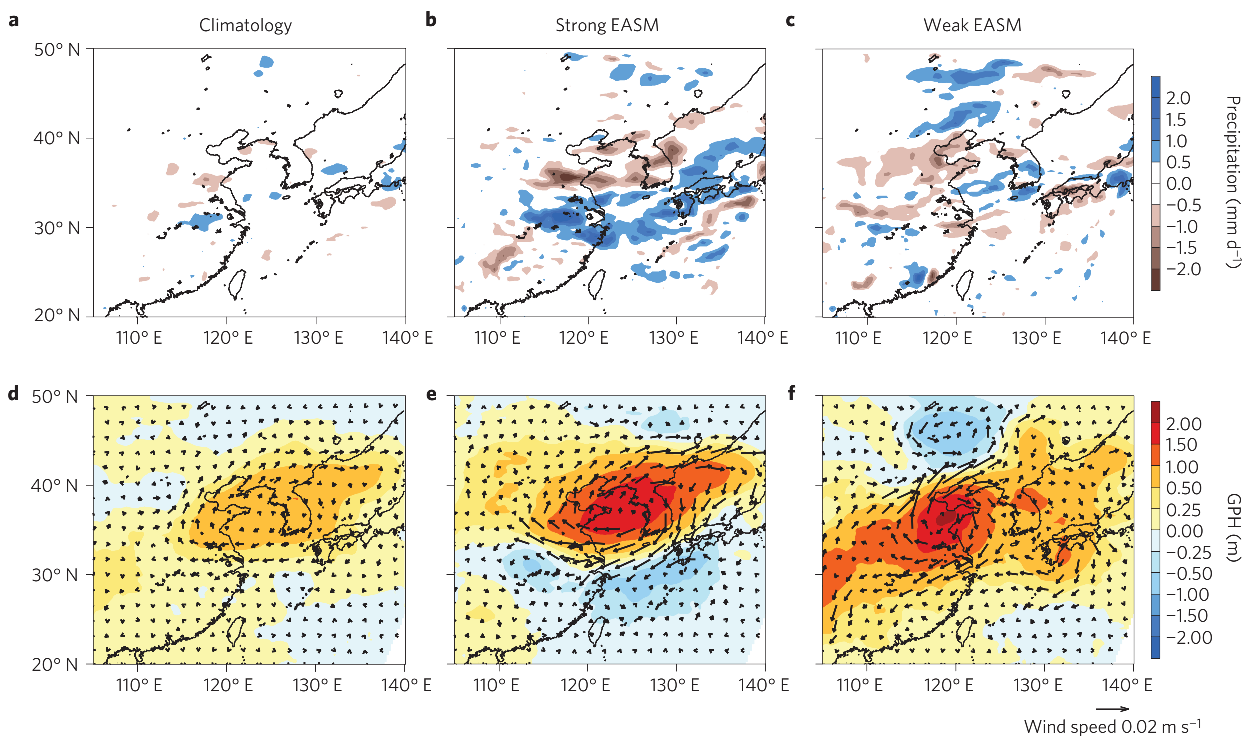

Figure 4 | Simulated impacts of double cropping on the NCP on precipitation and circulation over East Asia. a–c, Simulated differences between precipitation in the control (CTR) and experiment (EXP) over East Asia in: climatology, strong East Asian summer monsoon (EASM) and weak EASM, respectively. **d–f**, Simulated differences between the geopotential height (GPH; shading) and wind at 850 hPa (vectors) in the CTR and EXP over East Asia in: climatology, strong EASM and weak EASM, respectively.

regional precipitation changes are closely related to the anomalous circulation induced by the surface heating over the NCP due to the bare soil condition during the inter-cropping periods; enhanced anomalous circulation (Fig. 4e) leads to intensified oceanic inflow and increased precipitation in the southern NCP region (Fig. 4b). This anomalous circulation also contributes to the increase in precipitation around 30° N from southern China to Japan.

In contrast to the southern NCP region, precipitation in the northern NCP region decreases in response to double cropping. The precipitation change in the northern NCP may be explained by two factors. The decrease in evapotranspiration over the NCP during the inter-cropping period (that is, decreased LH in Fig. 3) reduces moisture supply for precipitation in the northern NCP region, which is strongly affected by local moisture recycling[15]. Previous land–atmosphere interaction studies[16,17] showed that the NCP region is one of the regions in the world with the strongest land–atmosphere coupling, including the effects of the moisture anomaly on local precipitation, particularly in the summer monsoon season[18]. In addition, the anomalous circulation induced by the heating in the inter-cropping period increases the inflow into the northern NCP region from the NCP region where evaporation decreases. These two effects of the anomalous heating in the inter-cropping period work together to result in decreased precipitation in the northern NCP region as a result of reduced moisture supply.

During weak EASM years, the anomalous circulation induced by the anomalous heating is confined to the Shandong Peninsula region. The increased northeasterly components have only a short fetch over the sea, resulting in much less moisture enhancement (the circulation may even enhance the transport of dry air from the land area over northern China) compared to that during the anomalous circulation during the strong EASM years (Fig. 4e,f). Thus, precipitation in the southern parts of the NCP is not affected much, or it decreases. The anomalous circulation increases the inflow into the northern NCP region from the inland area, resulting in a decrease in precipitation in the region. Regarding the climatology (Fig. 4a,d), statistically significant precipitation changes occur only in the northern NCP region. The precipitation decrease in the northern NCP region due to double cropping occurs regardless of the EASM phase because the anomalous circulation induced by double cropping increases the inflow into the region from the inland area, where evaporation is decreased during the inter-cropping period, and local evapotranspiration plays an important role in precipitation over the NCP region.

The simulated precipitation and winds over Korea and Japan show unexpected changes via interactions between cropland management over the NCP and the regional EASM system. It is noteworthy that the regions where precipitation changes occur are also generally the rain-fed agricultural areas[19], suggesting that large-scale agricultural practices will, in turn, affect agricultural land in other regions beyond the regional boundaries where such cropland management changes occur. The changes in winds and precipitation in the modelling study may be model-dependent, given that details of the simulated circulation and precipitation vary according to the model used, primarily due to uncertainties in the models' formulations[20]. Nevertheless, the consistency between the simulated and observed surface temperature changes in the present modelling results suggest that the climate in a specific agricultural region is affected not only by the local environment but also by remote environments. Thus, any quantitative assessment of agricultural impact on climate should be performed with an inclusion of the above-mentioned effects.

Methods

Single and double cropping regions over the NCP. After detecting croplands over the entire NCP region using the land-cover classification from the Global Land Cover Facility[21], SCRs and DCRs within the total cropland are identified. To identify these two different cropping practices, we use the LAI from the Advanced Very High Resolution Radiometer for the period 1985–2005 (ref. 22). The satellite LAI data starts from 1985, at which point double cropping practices were well established in the NCP region. That is, double cropping in the NCP started before the starting measurement date of the satellite data used for identifying the region. Because no record of exact double cropping areas is available, the satellite data is the only means of identifying cropping practices in the NCP. Seasonal variations in the growth of wheat and maize are well demonstrated in the LAI time series. The double and single LAI peaks in the DCRs and SCRs, respectively, can be identified from the LAI annual cycle (Supplementary Fig. 1). For the double LAI peak, the early maximum occurs in April–May, and the late maximum occurs in August. The single LAI peak occurs in August. More details are described in a previous study[9]. Based on these different characteristics of the LAI annual cycle, out of a total of 51 World Meteorological Organization stations on the NCP, 25 stations and 26 stations are grouped into DCRs and SCRs, respectively. The 21-year climatology of the surface air temperature variables T_{mean}, T_{min}, T_{max} and DTR over the DCRs and SCRs in Fig. 2 are defined by averaging the corresponding variables over the stations identified in this way for the entire study period.

Changes in crop area and yield. The changes in crop area over NCP are calculated using the historical changes in global land cover data[23] (Fig. 1a). The 16-year analysis period in this study (Fig. 1b), 1995–2010, has been selected because the official crop-yield data[8] used to support increased crop yields in the double cropping regions is available from 1995. It is extremely difficult, if not impossible, to exactly match historical records of crop area, yield and LAI-based double cropping. Thus, we have used all available data sets, even if they cover different time periods.

Regional climate simulations. The Advanced Research version WRF 3.3 (ref. 24) is used to investigate the impacts of the cropping practice in the NCP (20°–30° N, 112°–122° E) on the regional climate of East Asia. The one-way nested WRF model simulation is configured with a 54-km horizontal resolution and 27 vertical layers between the surface and the model top level (70 hPa). The model domain covers an East Asia region with a grid nest of 144 (East–West) ×74 (South–North) grid points on the Arakawa C-grid system. Seasonal simulations are performed over an eight-month (January–August) period for the 21 years, 1985–2005, using initial and lateral boundary conditions from the National Centers for Environmental Prediction-Department of Energy Reanalysis 2 (ref. 25). To examine the impact of the initial conditions on the simulated climate, four simulations are performed using four different initial conditions over four subsequent days. Because the four simulations generate similar climatology (not shown), results from only one of the four simulations are used in this study. For example, the inter-member standard deviation over the NCP is 0.04 °C for temperature and 0.03 mm d^{-1} for rainfall, whereas the differences due to the effects of double cropping are much larger than these inter-member standard deviation values at the 95% confidence level.

To isolate the impact of double cropping, we performed WRF simulations using two different annual cycles of the LAI based on satellite observations (Supplementary Fig. 1) over the NCP for the same initial and lateral boundary forcing. In particular, we tested the hypothesis obtained from the observation (Fig. 2) that the DCRs have a climatologically higher temperature than the SCRs owing to the absence of vegetative cover during the inter-cropping period. The CTR (EXP) simulation is prescribed with single (double) cropping LAI over croplands within the NCP. Thus, the difference between these two runs originates only from the impact of the prescribed vegetation seasonality differences over the NCP. The actual effect of the transition from single cropping to double cropping on the regional climate will be the difference between the results of these two simulations. For evaluation (Fig. 2), the simulated values at the grid points closest to the 51 stations are used (Fig. 3).

Analysis of East Asian summer monsoon (EASM). The inter-cropping period corresponds to the active EASM period. To investigate the impact of double cropping on the East Asian summer monsoon, strong- or weak-monsoon years are identified using the western North Pacific monsoon index[26]. This results in six strong EASM years (1988, 1993, 1995, 1996, 1998, and 2003) and five weak EASM years (1985, 1986, 1990, 1994, and 1997), for which strong- and weak-monsoon composites are constructed. The observed synoptic circulation and rainfall for the 21-year period during strong or weak EASM years are also investigated using reanalysis[25] and Global Precipitation and Climatology Project (GPCP) data[27]. These observed data are used as the basis for analysing and evaluating the simulated climatology for strong or weak EASM years (Supplementary Fig. 2).

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Author contributions

S-J.J. and C-H.H. designed the study. S-J.J., C-H.H. and Y-B.L. analysed the data and performed model simulations. All authors wrote the manuscript, discussed the results and implications, and commented on the manuscript at all stages.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C-H.H.

Competing financial interests

The authors declare no competing financial interests.